optical Communication system

Lec (1)

spectrum of Communication

1 — 200 m Hz — 30 GHz — 300 G — 30 t — 300 t — 3000 t Hz

Radio freq by Coaxial Cable

microwave waveguide

transperant material Air , water , Glass

1- has short transmision

2- Clear pure 20 dB/Km

$P_o = \frac{P_i}{100}$

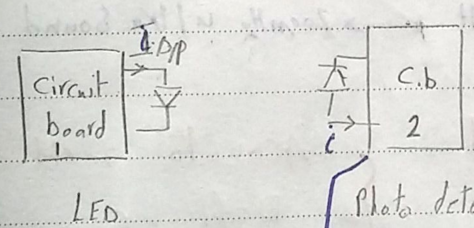
* $Q = \frac{f_o}{BW}$ $BW = \frac{f_o}{Q}$

* optical window At Range of T.Hz

Comm . sy

Small Range — large range

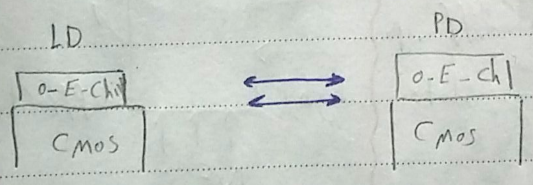
①



with electrical isolation

② VCSL vertical Cavity surface Tx laser

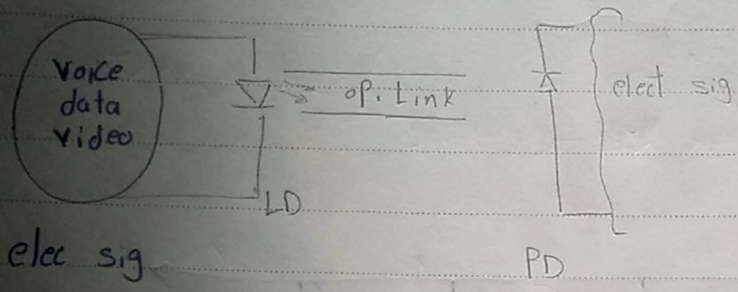
②



O.E-Ch = opto electronic chip

Reference: ① J. Singh / electro / optic elec
Proparities semi conduct (1995)
② - Fundemental of Photonic
Saleh (2007)
③ keiser (2009)
fiber optic Comm

③ optical fiber Comm:



* the 3 type Called opto electronic devices (optical electronics) that involved Light interaction
ex: LD , PD , PT , Solar cell

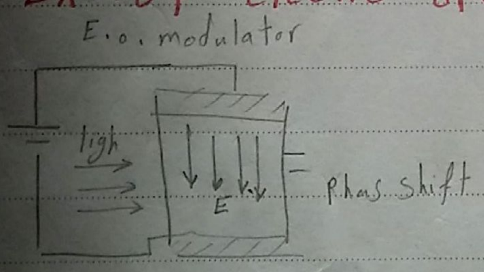
* - electro optic : is device or system where this Characteristic alternate by electric fild
n - ε_r - μ_r

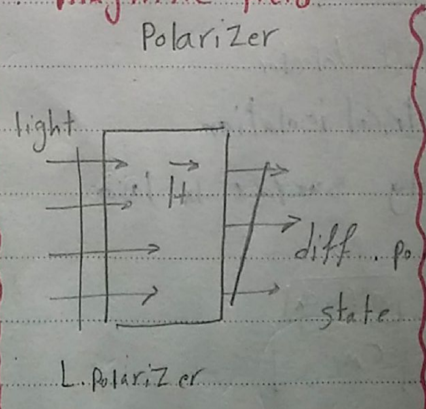
2 - magnetic optic : alternate by magnetig fied

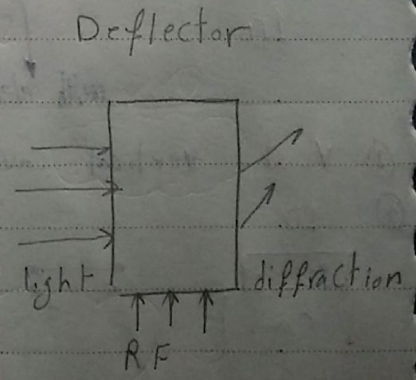
3 - Aconsto optic : " " Sound

1 Hz → 20 Hz infra Sound
20 Hz → 20 kHz Audiable
20 kH → 200 mHz ultra Sound

Ex. of electro optic, magnitic field, Aconsto field







Photonics:

optical electronic + fiber Comm + optical signal Processing
+ integrated optics

* all opto eletronic devices Based on Sami Conductor

$\boxed{\text{insolator}}$ $\boxed{\text{S.C}}$ $\boxed{\text{metal}}$

$\boxed{\sigma}$ $10^{-12} - 10^{-18}$ s/cm $<$ $10^{-6} \rightarrow 10^{3}$ $<$ $10^{4} \longrightarrow 10^{7}$ s/cm

* $E = KT =$
$= 1,38 \times 10^{-23}$ / $T = 300$ kv

$E = 25$ m ev At room temprature

Conductivity by semi Conductor Can be modified by

- Tempretur
- illumination
- Dopping

Course:

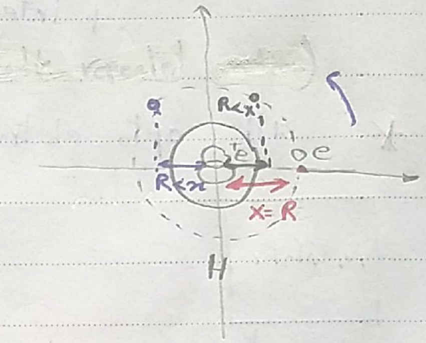
1) - electrical & optical Proparties of s.c (Energy gap - EK - diagram)
2) - interaction of ligh with s.c (Absorption - Emission ......)
3) - Devices (Photo diod - solar Cell ......)
4) - fiber link (SNR - WDM) - Net working)

/ . /

Lec (2)

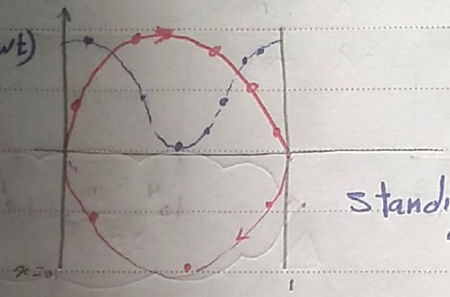
Energy band of semi Conductor

* the electron has periodic repeated motion
* we cant ~~det~~ denote the location of it



$\psi = \cos kx = e^{j(kx - wt)}$

$\psi = \sin Kx$



standing wave

* r denote the size of wave (Atom)

Deriving of shrodinger:

$\psi = e^{jkx}$

$E = \underbrace{\frac{1}{2} m v^2}_{\text{Kinetic}} + \underbrace{U}_{\text{Potention}}$ energy of electron

$P = mv \implies E_K = \frac{P^2}{2m}$, $E_p = U$

$\psi . E = \frac{P^2}{2m}\psi + U\psi$

$\frac{d\psi}{dx} = jk . e^{jkx}$

$\frac{d\psi}{dx^2} = -k^2 e^{jkx}$ * (1)

investigate

$K = \frac{P}{\hbar}$ wave vector

$\hbar = \frac{h}{2\pi}$

** (2)

* $V = \frac{w}{k} \implies r.f = \frac{2\pi . f}{k} \implies \boxed{K = \frac{2\pi}{r}}$

(2) in (1) $\implies \frac{d\psi^2}{dx^2} = \frac{-P^2}{\hbar} e^{jkx}$

$e^{jkx} \downarrow \psi$

$\implies \boxed{\frac{d\psi^2}{dx^2} = \frac{-P^2}{\hbar}\psi}$ (3)

$$P^2\psi = -\hbar^2 \frac{d^2\psi}{dx^2}$$ (4)

(4) in (3)　　$$\psi E = \frac{-\hbar^2}{2m} \cdot \frac{d^2\psi}{dx^2} + U\psi$$

H

$+ \overset{r}{\text{———}} -$

$$U = \frac{e^2}{4\pi\epsilon_0 r}$$

$$\Rightarrow \boxed{\frac{\hbar^2}{2m}\frac{d^2\psi}{dx^2} + (\overset{?}{E} - U)\psi = 0}$$ shrödinger equation

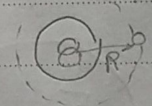
if Eign value $\frac{d\psi}{dx} = c\,\psi$

$$\frac{d^2\psi}{dx^2} = -\underbrace{(E - U)\frac{2m}{\hbar^2}}_{\text{Const}}\psi$$

Solution of shrödinger equation (Eign value = E):

- $\psi(x) = e^{jKx}$
- $\psi(x+L) = e^{jK(x+L)}$
- but $\psi(x) = \psi(x+L)$　　Periodic fun (At time + space)
- $L = 2\pi R$

$L = 2\pi R$



$$\Rightarrow e^{jKx} = e^{jK(x+L)} \Rightarrow e^{jKL} = 1 \Longleftrightarrow \cos(KL) = 1 \text{ oR } \sin(KL) = 0$$

$$\Rightarrow KL = n * 2\pi \quad \text{where } n = \mp 1, \mp 2, \mp 3\ \pi$$

$$\Rightarrow \boxed{K = \left(\frac{2\pi}{L}\right) n}$$

discrete value = quantized

$$\frac{2\pi}{\lambda} = \frac{2\pi}{L} n$$

$$\Rightarrow K = \frac{P}{\hbar} = \frac{2\pi}{L} n = \frac{2\pi}{2\pi R} n$$

dec Broslli
discrete value

$$\boxed{P R = n\hbar}$$

أي انه أي جسم مصاحبة عبه Wave

Wave Particle duality

$$\Rightarrow P = \left(\frac{n}{R}\right)\hbar \quad \Rightarrow$$

discrete value

$$\underbrace{mV}_{P} R = n\hbar \Rightarrow V^2 = \frac{n^2\hbar^2}{m^2R^2}$$

$$\Rightarrow \quad V^2 = \frac{n^2 \hbar^2}{m^2 r^2} \quad \triangle 1$$

$$F_c = \frac{e^2}{4\pi\varepsilon_0 R^2} = ma = m\frac{V^2}{R} \quad \triangle 2$$

bec: but $a = \frac{V^2}{R}$

$\triangle 2$ in $\triangle 1$
$$\frac{e^2}{4\pi\varepsilon_0 R^2} = \frac{m\, n^2 \hbar^2}{R m^2\, R^2}$$

but $\hbar^2 = \frac{h^2}{4\pi^2}$

$$\Rightarrow \quad R = \frac{n^2 h^2 \varepsilon_0}{\pi m e^2} \quad \triangle 3$$

discrete Value

$$V = \frac{e^2}{2m^2 h \varepsilon_0} n$$

from section

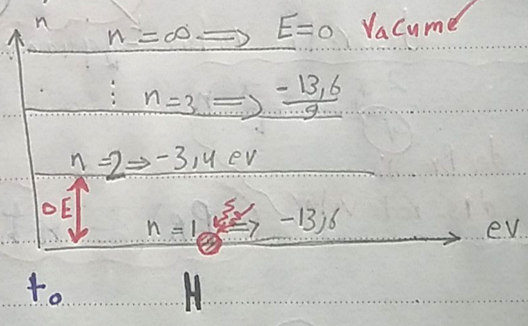
$\triangle 1$ in * $E = \frac{1}{2} m V^2 + U$

$$\Rightarrow \quad E_k = \frac{1}{2} m \frac{n^2 \hbar^2 \pi^2 m^2 e^4}{m^2 \times n^4 \cdot h^4 \varepsilon_0^2\, 4\pi^2}$$

$$E_k = \frac{e^4 m}{8 n^2 h^2 \varepsilon_0^2}$$

$\triangle 3$ in
$$U = E_p = \frac{-e^4 \pi m}{4\pi \varepsilon_0^2 n^2 \cdot h^2}$$

$$E = -\frac{e^4 m}{8 \varepsilon_0^2 n^2 h^2} = -\frac{13{,}6}{n^2}$$



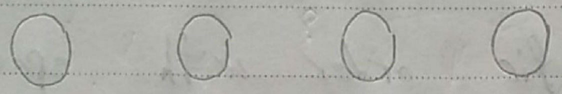
n=1 ground state

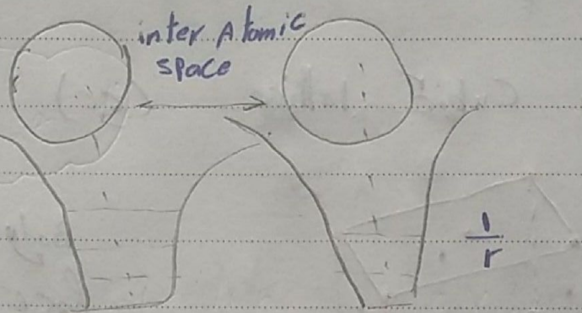
⟹ the material is transperent material absorbe discrete (denoted) energy to change the energy level

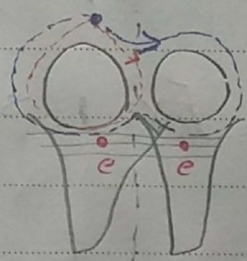
Energy band = Not allowed energy level

Lec (3)

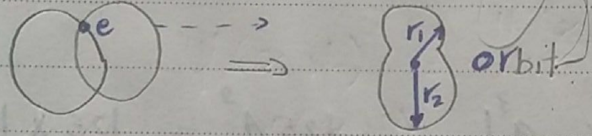
ATOms in Solid material:

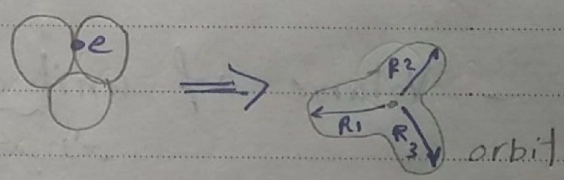


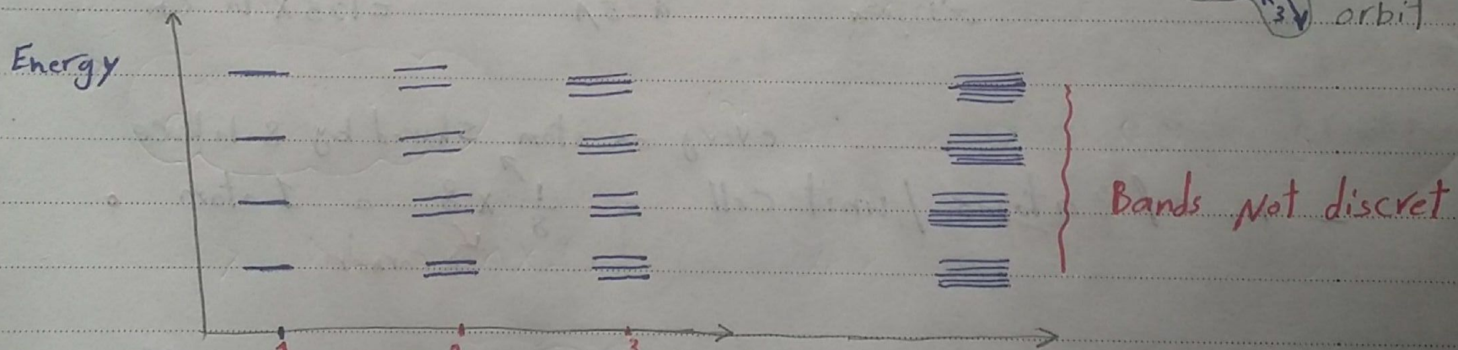




electron has 2 path
2 orbit

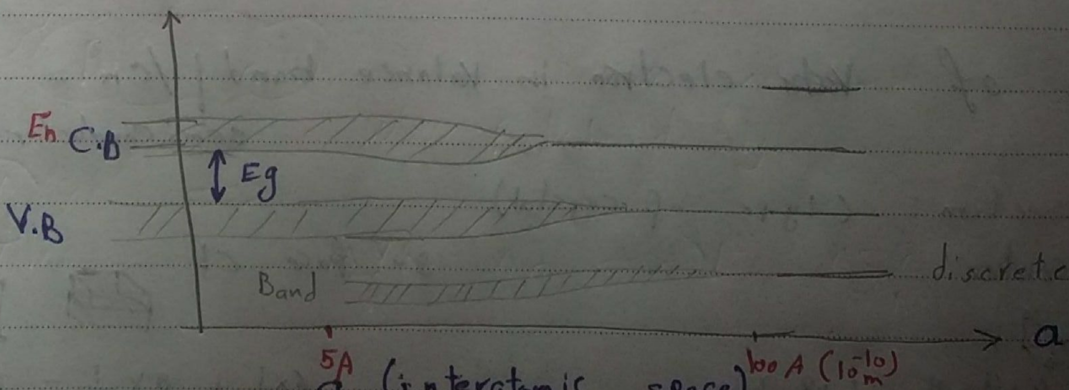






No of ATOms (interacting)

Energ level for electron around ATOMs



a (interatomic space)

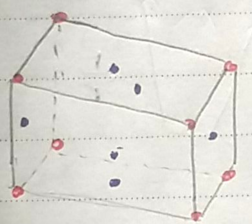
* semi Conductor $7A > a > 3A$

semiConductor

1- Crystals:

atoms aligned on specific order with specific seperation

Ex: 1- Simple Cubic lattice (sc)



Body sc

face sc

- Volume of unit cell $= a^3 \,|\, a = 5A$ $= 125 A^3 = 125 \times 10^{-30}\ m^3$ $= 125 \times 10^{-24}\ cm^3$

مكعب واحد

every on atom shared by 8 lattice

- n. of atoms / unit cell $= \frac{1}{8} \times 8 = 1$ atom

8 Corner

- n of atoms / Cm^3 $= 1 / 125 \times 10^{-24}\ Cm^3 = 10^{22} / cm^3$

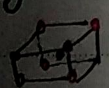
أي أنه يوجد في المواد شبه الناقلة 10^{22} ذرة في $1 cm^3$

- n of ~~Vala~~ electron in Valance band | $/ Cm^3 = 10^{22} \to 10^{23} / Cm^3$

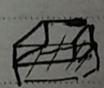
semi Conductor

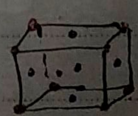
* from Section: (type of crystal)

2- Body center



3- face CL

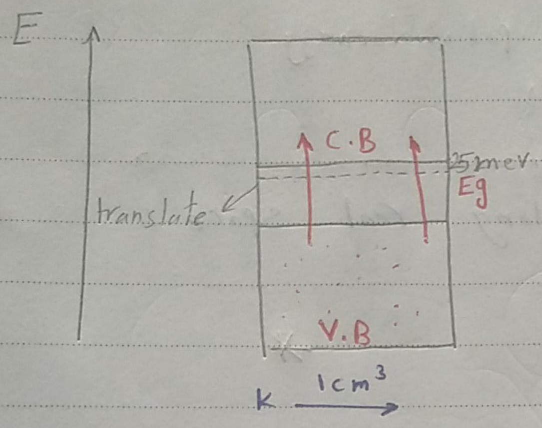




n. of atom / unitcell $= \frac{1}{8} \times 8 + 1 = 2$

$6 \times \frac{1}{2} + 8 \times \frac{1}{8} = 4$

Band ~~ga~~ diagram:



$E_g = 0{,}67\ ev$ for Ge

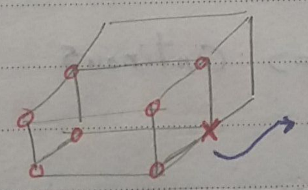
$E_g = 1{,}1\ ev$ " Si

$E_g = 1{,}42\ ev$ " GA AS

⟹ - semi Conductor material at $T_o = 0K$ ⟹ insulator (No free Carier)

- semi Conductor at $T = 300\ K$ $E = KT = 25\ mev$

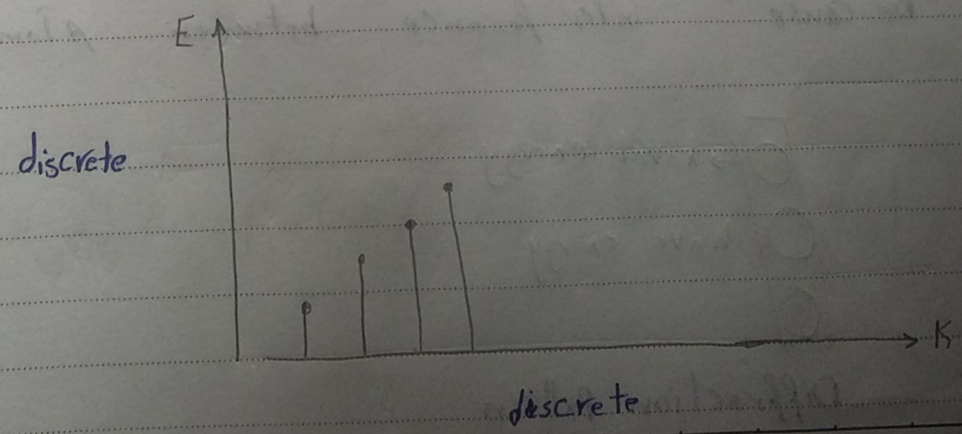
* no. of Ge ATom At room temp = $10^{13} / cm^3$ because Defects in material (not pure)



* $E_g = 1 \rightarrow 3\ ev$ for semi conductor / $E_g > 4\ ev$ for insulator Conductor

approximate value

E _ K diagrame (band structure oR Dispersion diagrame)



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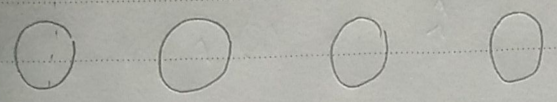
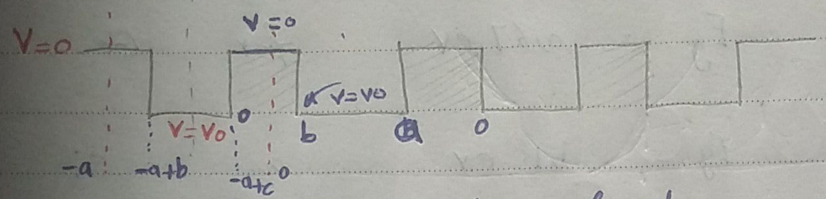


Periodic no. of Atom (crystal)



potintial energy

u = PE = Periodic function along real space

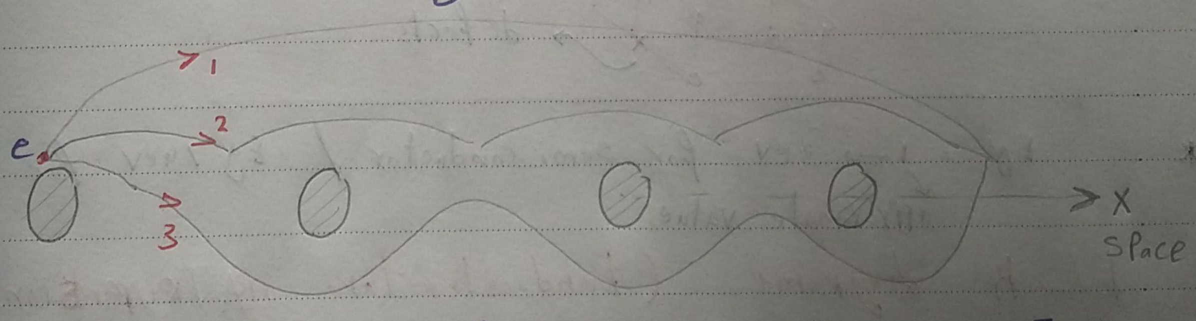
$$u = \begin{cases} V = V_0 & a > x > b \\ V = 0 & b > x > 0 \end{cases}$$

$$\frac{\hbar^2}{2m} \cdot \frac{d^2\psi}{dx^2} + (E - u)\psi = 0 \quad (1)$$

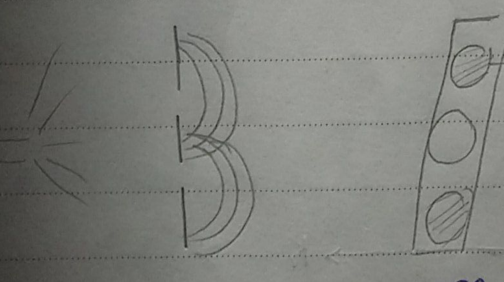
$u = 0$ $\qquad\qquad$ $u = V_0$

ψ_1 $\qquad\qquad$ ψ_2

$\Downarrow \Longrightarrow$ Propability => Continous



be cause inter ferance between ATOMs



Diffraction Pattern

E - k diagrame: interaction between allowed energy level (electron wave) with the Periodicety of Crystal

* $U = 0 \overset{①}{\Longrightarrow} \dfrac{\hbar^2}{2m} \dfrac{d^2\psi_1}{dx^2} + E\psi_1 = 0$

$$\frac{-\hbar}{2m} \frac{d^2\psi_1}{dx^2} = E_1 \psi_1$$

Assume $\boxed{\psi_1 = A e^{jkx}}$ △1

$$\Longrightarrow \frac{d^2\psi_1}{dx^2} = -k^2\psi_1 \Longrightarrow$$

$$\Longrightarrow E_1 = \frac{\hbar^2 k^2}{2m}$$ *

$0 < x < b$

* $U = V_0 \overset{①}{\Longrightarrow} \dfrac{\hbar^2}{2m} \cdot \dfrac{d^2\psi_2}{dx^2} + (E - V_0)\psi_2 = 0$

$$\frac{\hbar^2}{2m} \cdot \frac{d^2\psi_2}{dx^2} = \underbrace{(V_0 - E)}_{+ve}\psi_2$$

Assum $V_0 >> 0$

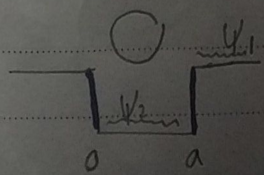
assume: $\boxed{\psi_2 = B e^{\sigma x}}$ △2

$$\Longrightarrow \frac{d^2\psi_2}{dx^2} = B\sigma^2 e^{\sigma x} = \sigma^2 \psi_2$$

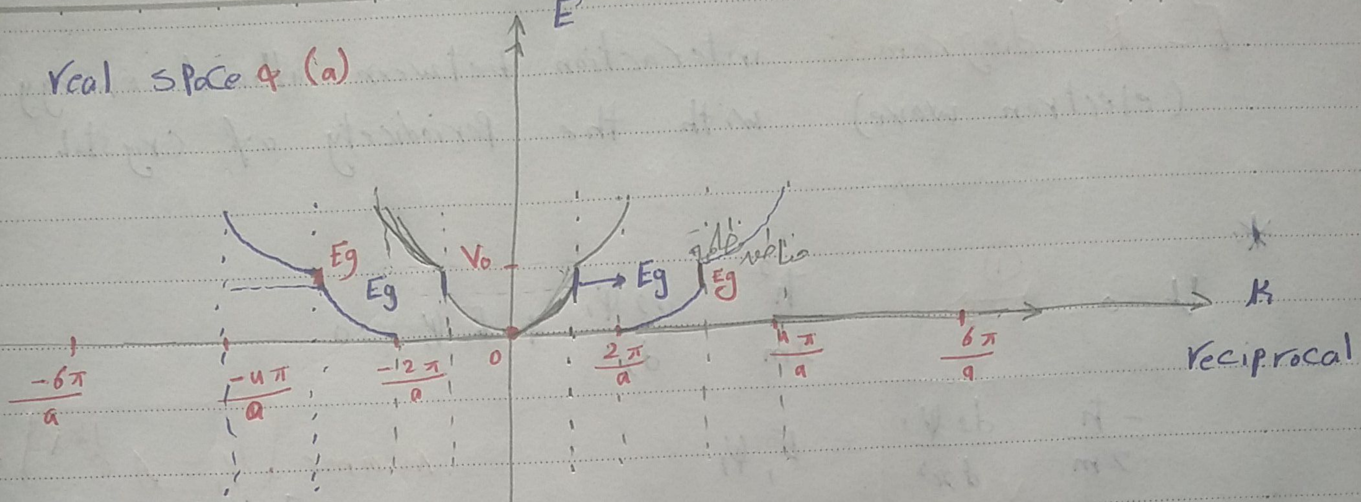
$$\Longrightarrow \boxed{E_2 = V_0 - \frac{\hbar^2 \sigma^2}{2m}}$$ **

$\Longrightarrow \psi_1(x=0) = \psi_2(x=0) \Longrightarrow A = B$

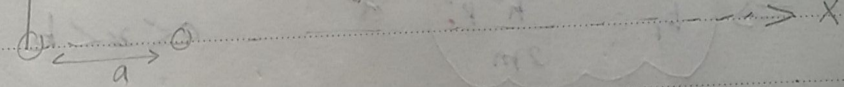
$\psi(x=a) = \psi_2(x=a) \Longrightarrow \sigma = jK$



from * 8 * *



Reciprocal space $\propto (\frac{1}{a})$



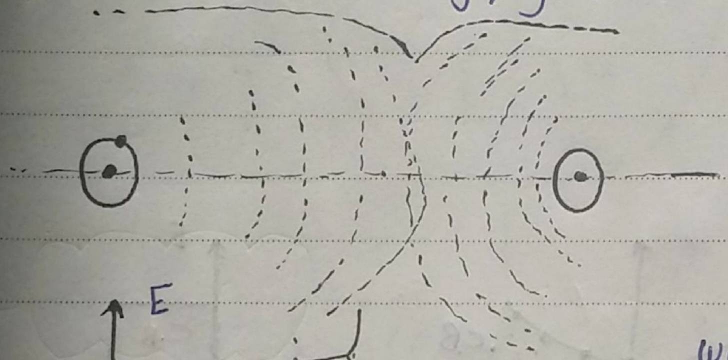
$\psi_1(\cancel{x=0}\, x) = \psi_1(x \mp a)$ | At $e^{jka} = 1$ OR $k = \frac{N \times 2\pi}{a}$ $N = 0, \mp 1, \ldots$

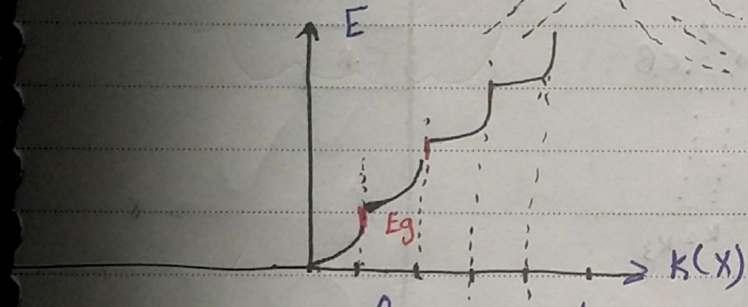
/ /

Lec (4)

E - k diagrame:

Relation between Energy & k

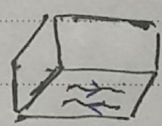




space for one atom

$\psi(x=0)=0$

$\psi(x=L)=0$



$\psi_1 = Ae^{jkx} + Be^{-jkx}$

$\psi = \sin(kx)$

$$\psi(x=0) = Ae^{jkx_0} + Be^{-jkx_0} = 0$$

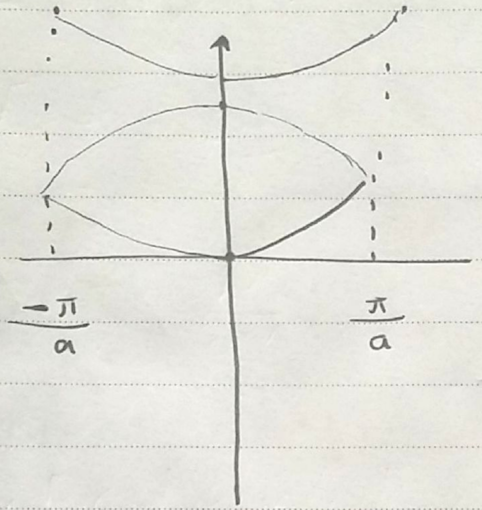
$$\Longrightarrow \quad A = -B$$

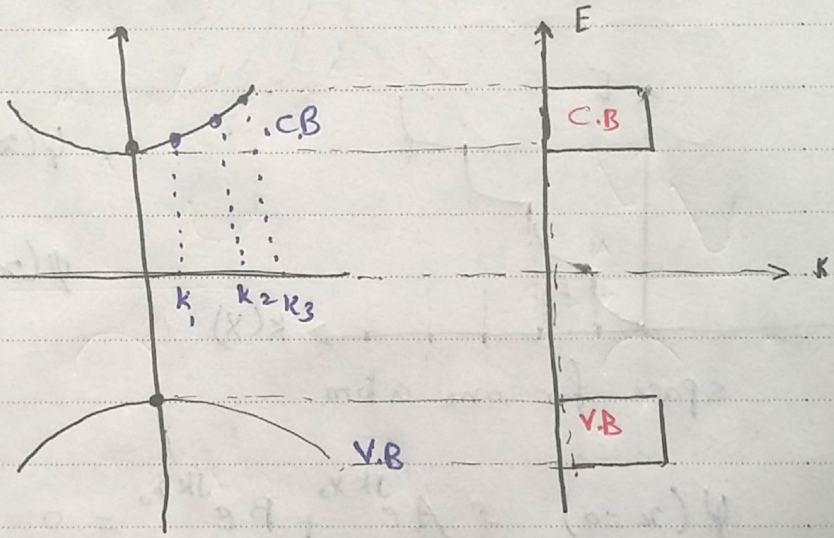
$$\psi(x=L) = Ae^{jkL} - Ae^{-jkL} = 2A\sin(kL)$$

$$2A\sin(kL) = 0 \Longrightarrow \sin(kL) = 0$$

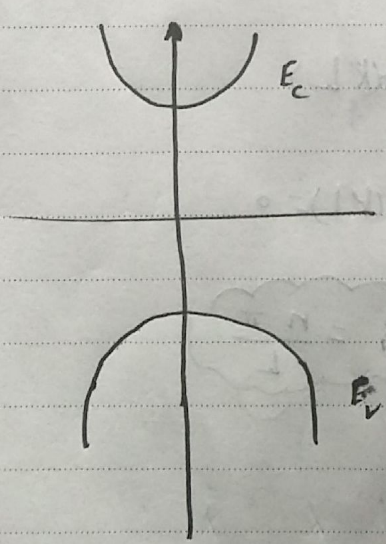
$$kL = n\pi \Longrightarrow k = \frac{n\pi}{L}$$

3)- Reduced zone



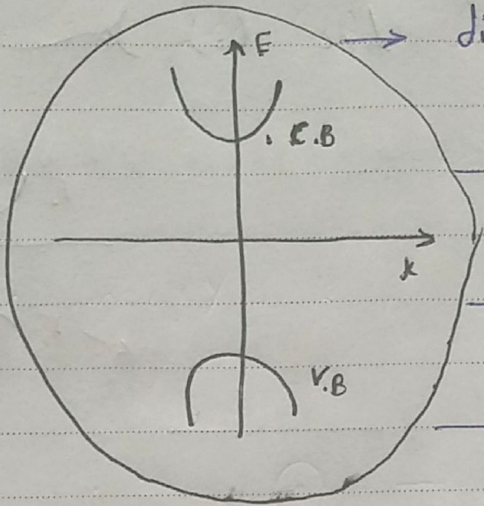


Parapolic approximation



$$E = E_c + \frac{\hbar^2 k^2}{2m_c}$$

$$E = E_v - \frac{\hbar^2 k^2}{2m_v}$$



$\rightarrow$ direct & indirect semi Conductor

$\rightarrow$ group velocity

$\rightarrow$ effictive mass

$\rightarrow$ mobility $\mu \propto \frac{1}{m_c}$

$\sigma = nq\mu$

carrier concentration

$$n = \int_{E_c}^{\infty} g(E) \cdot f(E) \cdot dE$$

density of state

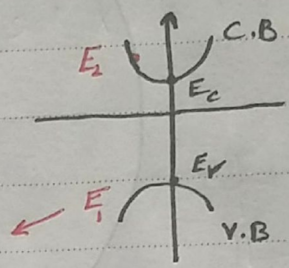
probability of accuration

Lec (5)

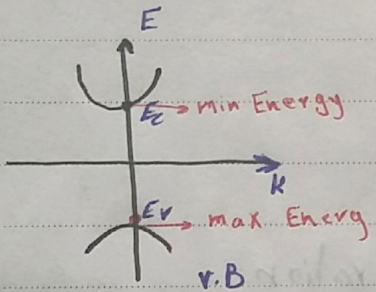
E–K diagrame:

$$E_2 = E_c + \frac{\hbar^2 k^2}{2m_c}$$

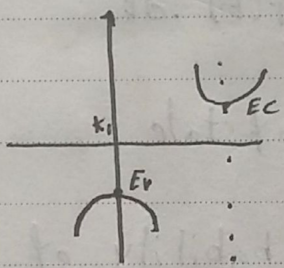
$$E_1 = E_v - \frac{\hbar^2 k^2}{2m_v}$$



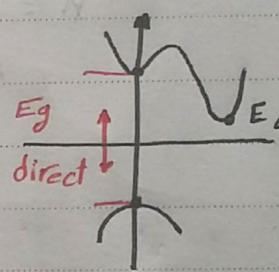
1) Direct & indirect semi conductor:



Direct



indirect



indirect

Maximum of V.B Energy & minimum of C.B accure at the Sam K

maximum value of Energ At V.B has different K to the minimum value of Energy at C.B

$E \Rightarrow KE = \frac{1}{2} m v^2$

$P = \hbar k$ = momentum = mv

Assume:

$m_1 = 10kg$ $\quad V_1 = 1 m/s$

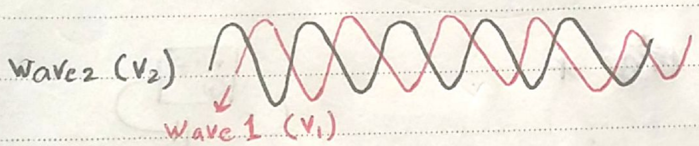
$KE_1 = \frac{1}{2} \times 10 \times 1^2 = 5J$ $\Big\} \Rightarrow P_1 = 10 \; kg\, m/s$

/ /

Ex: (2) $m_2 = 1g$ $V_1 = \sqrt{\frac{5}{0{,}5 \times 0{,}001}} = \sqrt{1000}$

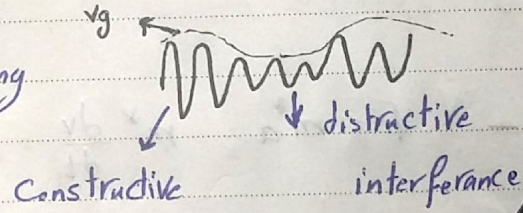
$\Longrightarrow P = \sqrt{1000} \times 0{,}001 \; kg \; m/s$

2) - group Velocity (V_g) :



Beats

V_g = speed of the envelope Traveling wave (Beat).



$$E = E_c + \frac{\hbar^2 k^2}{2m_c}$$

$$\frac{\partial E}{\partial k} = \frac{2\hbar^2 k}{2m} = \frac{\hbar^2 k}{m_c} = \frac{\hbar k \hbar}{m_c}$$

$$\frac{\partial E}{\partial k} = \frac{\hbar}{m_c} \cdot m_c v = \hbar . v$$

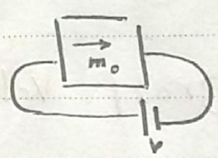
$$\boxed{V_g = \frac{1}{\hbar} \cdot \frac{\partial E}{\partial k}} \Longrightarrow \boxed{V_g = \frac{\partial w}{\partial k}} \text{ because}$$

$$V_g = \frac{1}{\hbar} \frac{\partial E}{\partial k} = \frac{1}{\hbar} \frac{\partial h f}{\partial k} = \frac{h}{\hbar . 2\pi} \cdot \frac{\partial 2\pi f}{\partial k} = \frac{\partial w}{\partial k}$$

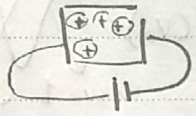
/ /

3) - effective mass :

electron has m_o (rest mass) $= 9.1 \times 10^{-31}$ kg
without internal force

$\Longrightarrow F_{ext} = m_o\, a \rightarrow \frac{dv}{dt}$ $\Leftarrow$ E  external

if we have $F_{internal}$

$F_{net} = F_{ext} + F_{int} =$ * 

$\Longrightarrow \boxed{F_{ex} = m^* a}$ $\qquad m^* < m_o$

- $F = m^* a = m^* \frac{dv}{dt}$ $\qquad$ but $v = \frac{1}{\hbar} \cdot \frac{\partial E}{\partial k} \Rightarrow$

$\Downarrow$

$\Longrightarrow dv = \frac{1}{\hbar} \frac{\partial^2 E}{\partial k}$

$$\boxed{F = m^* \cdot \frac{1}{\hbar} \frac{\partial^2 E}{\partial k . dt}} \quad (1)$$

مسافة

- $dE = F . dx = F . dv . dt$

$\Longrightarrow dE = F . \frac{1}{\hbar} \frac{d^2 E}{dk . dt} . dt^2$

$\Longrightarrow dE = F . \frac{1}{\hbar} \frac{\partial^2 E}{\partial k} . dt$

$\Longrightarrow \boxed{F = \hbar\, dk/d.dt} \quad (2)$

(1) + (2)

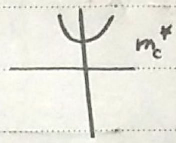
$$\boxed{m^*_e = \frac{\hbar^2}{\partial^2 E / \partial k^2}}$$

bec $\frac{\hbar . dk}{\partial . dt} = m^* . \frac{1}{\hbar} \frac{\partial^2 E}{\partial k . dt}$

/ /

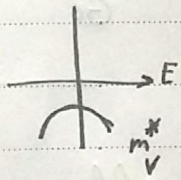
OR $E = E_c + \frac{\hbar^2 k^2}{2m_c}$

$$\frac{\partial^2 E}{\partial k^2} = \frac{2\hbar^2}{2m_c} = \frac{\hbar^2}{m_c} \Rightarrow \boxed{m_c^* = \left(\frac{\partial^2 E}{\partial k^2}\right)^{-1} \cdot \hbar^2}$$



if

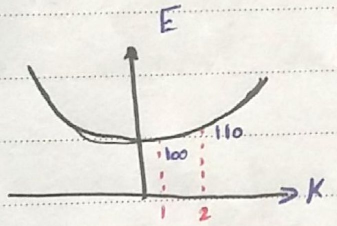
$$E = E_v - \frac{\hbar^2 k^2}{2m_v}$$

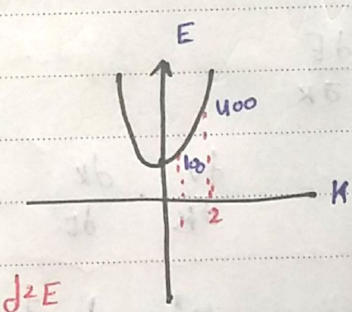


$$\frac{\partial^2 E}{\partial k^2} = -\frac{\hbar^2}{m_v}$$

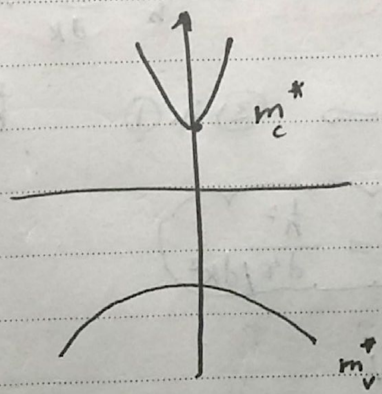
$$\Rightarrow m_v = -\left(\frac{\partial^2 E}{\partial k^2}\right)^{-1} \cdot \hbar^2$$

curvature





$$\frac{\partial^2 E}{\partial k^2} \ll \frac{\partial^2 E}{\partial k^2}$$



$m_c < m_v$

$\Rightarrow$ to move electron from V.B to C.B we need higher energy than move it at C.B

/ /

Ex:

	m_e^* / m_c^*	m_h^* / m_v^*
Si	$0,98\ m_0$	$0,49\ m_0$
Ge	$0,08\ m_0$	$0,28\ m_0$

at room temp

effi

Lec (6)

3) effective mass

$$V = \frac{1}{\hbar}\ \frac{dE}{\partial k}$$

$$a = \frac{dv}{\partial t} = \frac{dv}{dk} \cdot \frac{dk}{dt} = \frac{1}{\hbar}\ \frac{d^2E}{dk^2} \cdot \frac{dk}{dt}$$

$$F = m^* a = m^* \cdot \frac{1}{\hbar}\ \frac{\partial^2 E}{dk^2} \cdot \frac{dk}{dt} \quad (1)$$

$$dE = F \cdot dx \Rightarrow dE = F \cdot \frac{1}{\hbar}\ \frac{dE}{\partial k} \cdot dt \quad (2)$$

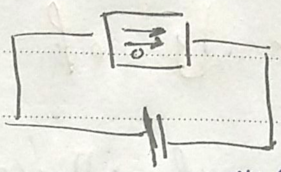
$$F = \hbar\ \frac{dk}{dt} \quad (3) \quad \Rightarrow (3) \text{ in } (1) \quad \hbar\ \frac{dk}{\partial t} = \frac{m^*}{\hbar} \cdot \frac{d^2E}{dk^2} \cdot \frac{dk}{dt}$$

$$\boxed{m^* = \frac{\hbar^2}{d^2E/dk^2}}$$

4) Carrier mobility :
ability of carrier (electron - hole) to move in response to electric field

/ /

$\mu = \frac{V_d}{E} = \frac{q}{m^* F_c}$



q = electron Charg

f_c = freq of Collision

$\mu = \frac{q\,T_c}{m^*}$ → average Collesion Time $= \frac{1}{f_c}$

EX:

given:

$E_2 = E_c + \frac{\hbar^2 (k-5)^2}{2m_c}$, $E_1 = E_v - \frac{\hbar^2 k^2}{2m_v}$

$m_c = 0.2 m_0$, $m_v = 0.8 m_0$, $m_0 = 9.1 \times 10^{-31}$ kg

$E_g = 1.6\,eV$

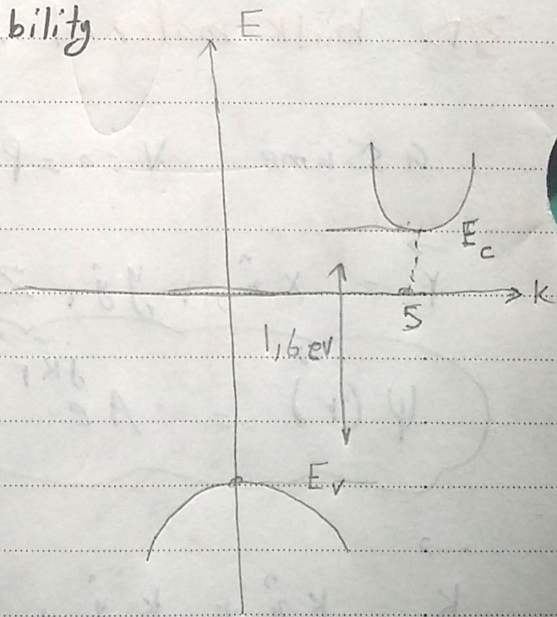
1) Draw qualititvely the E-k digram

2) - Comment on directivity and mobility

indirect semiconductor

$\mu_c > \mu_v$ because

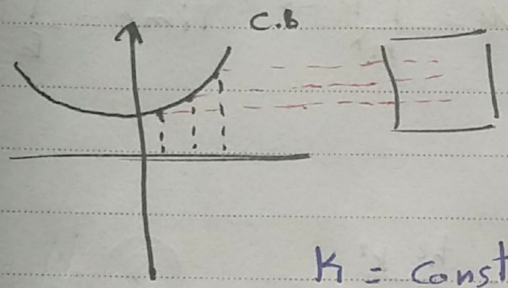
$\mu \propto \frac{1}{m^*}$



/ /

4) - Denesity of state $\rho(E)$:

number of allowed state / unit Volume



0D Quantum dot

1D Non wire

2D Surface

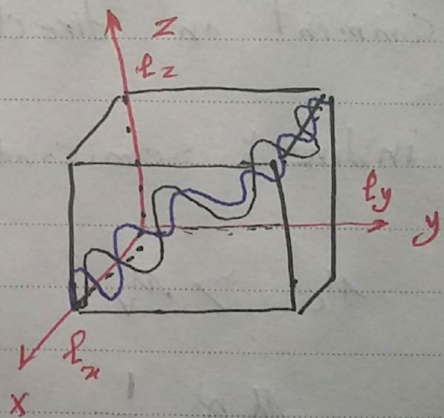
3D Bulk

$K = \text{Const} \Rightarrow$

$\Rightarrow E = \text{Const}$

* $\rho(E) \longrightarrow$ depend on K- space

3D bulk material :



assume $V = 0 = P.E$

$$\vec{r} = x\hat{x} + y\hat{y} + z\hat{z}$$

$$\psi(\vec{r}) = A e^{j\vec{k}\vec{r}} + B e^{-j\vec{k}\vec{r}}$$

$$\vec{k} = k_x\hat{x} + k_y\hat{y} + k_z\hat{z}$$

$$\psi(\vec{r}) = A e^{j(k_x x + k_y y + k_z z)} + B e^{-j(k_x \cdot x + k_y \cdot y + k_z \cdot z)}$$

Apply Boundaries Condition :

/ /

$\psi(0,0,0) = 0$ ①

$\psi(L_x,0,0) = 0$ ② , $\psi(0, L_y, 0) = 0$ ③ $\psi(0,0,L_z) = 0$ ④

$\Rightarrow A = -B$

$$\psi(r) = A\left(e^{j\ldots} - e^{-j\ldots}\right) = A^* \sin(k_x x + k_y y + k_z z)$$

$$x \to L_x, \quad y \to 0, \quad z \to 0$$

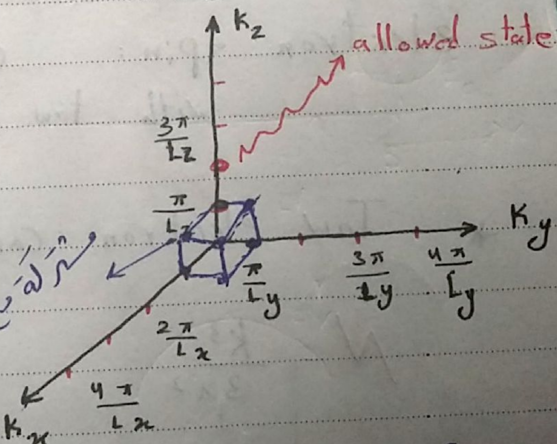
$$\Rightarrow \psi(L_x,0,0) = 0 = A^* \sin(k_x L_x) = \text{Zero}$$

$$\Rightarrow k_x L_x = m\pi \quad \Rightarrow \quad k_x = \frac{m\pi}{L_x}$$

integer

Similary: $k_y = \dfrac{P\pi}{L_y}$, $k_z = \dfrac{q\pi}{L_z}$

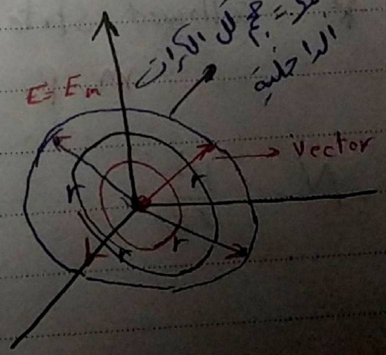
* P = integer



$$K = \sqrt{k_x^2 + k_y^2 + k_z^2}$$

Volume of one state: (specific energy)

$$\text{Volume} = \frac{\pi}{L_x} \times \frac{\pi}{L_y} \times \frac{\pi}{L_z} = \frac{\pi^3}{L_x . L_y . L_z}$$



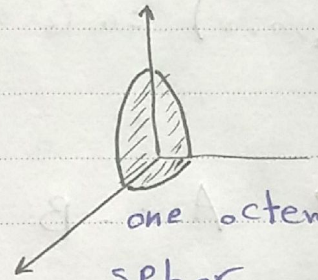
قيمة k ثابتة عند أي نقطة على الدائرة

K = const

$$K = \sqrt{k_x^2 + k_y^2 + k_z^2} = \text{const}$$

⇒ the volume of all allowed state up to E_n

$$\text{Volume} = \frac{4}{3} \pi K^3$$



$$\text{Volume} = \frac{1}{8} \cdot \frac{4}{3} \pi k^2$$

one octent of spher

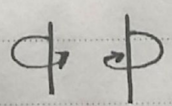
one allowed state (K_{+k} & k_{-k}

$$N \underset{L_x, L_y, L_z}{(\text{cubied})} = \frac{\frac{1}{8} \cdot \frac{4}{3} \pi k^2}{\pi^3 / L_x \cdot L_y \cdot L_z}$$

$$N = \frac{k^3 \, L_x \cdot L_y \cdot L_z}{6 \pi^2}$$ number of allowed state

$$N / \text{unit volum} = \frac{K^3}{6 \pi^2}$$

electron spin: electron rotate around its self with tow direction



* Tow electron can accumendate the same allowed state

$$N = \frac{K^3}{3 \pi^2}$$

* allowed state recognize by 4 quantum number
m, p, q, spin

$$N = \frac{k^3}{3 \pi^2}$$

$$\rho(E) = \frac{dN}{\partial E}$$

/ /

$$\int dN = \int \rho(E) \cdot dE$$

$$\Rightarrow \rho(E) = \frac{dN}{dE} = \frac{dN}{dk} \cdot \frac{dk}{dE} = \frac{k^2}{\pi^2} \cdot \frac{dk}{dE}$$ because $N = \frac{k^3}{3\pi^2}$

but $\frac{dk}{dE} =$ $E_c + \frac{\hbar^2 k^2}{2m_c}$, $E_v - \frac{\hbar^2 k^2}{2m_c}$

$\Rightarrow$ for c.b

$$\frac{dE}{dk} = \frac{\hbar^2 k}{m_c}$$

$$\Rightarrow \rho_c(E) = \frac{k^2}{\pi^2} \cdot \frac{m_c}{\hbar^2 k}$$

$$\rho_c(E) = \frac{m_c}{\pi^2} \cdot \frac{k}{\hbar^2} = \frac{m_c}{\pi^2} \frac{(E-E_c)^{\frac{1}{2}} (2m_c)^{\frac{1}{2}}}{\hbar^2 \cdot \hbar}$$

$$\rho_c(E) = \frac{1}{2\pi^2} \cdot \left(\frac{2m_c}{\hbar^2}\right)^{3/2} (E-E_c)^{\frac{1}{2}}$$

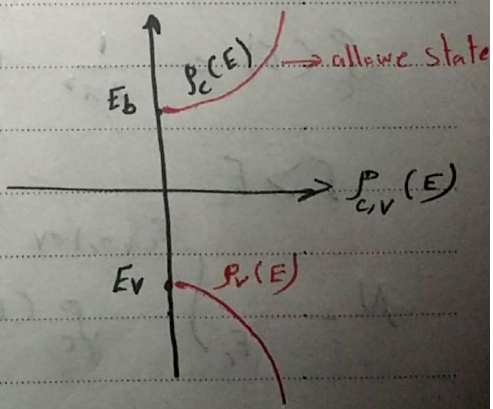
Similary

$$\rho_v = \frac{1}{2\pi^2} \cdot \left(\frac{2m_v}{\hbar^2}\right)^{3/2} (E_v - E)^{\frac{1}{2}}$$

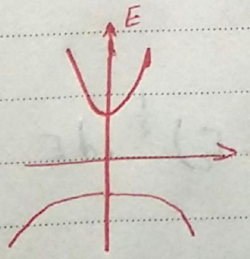
$\Rightarrow$

$\rho_c \propto m_c$

$\rho_v \propto m_v$



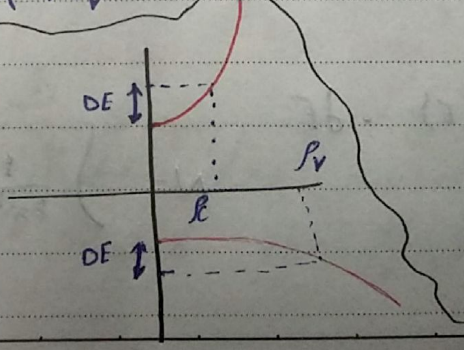
for EX:



$\Leftarrow$

$\rho_v > \rho_c$

$m_v > m_c$



/ /

Lec (7)

EX:

Given GaAS

$m_h = 0{,}45\ m_0$, $m_c = 0{,}067\ m_0$

$E_g = 1{,}42\ eV$

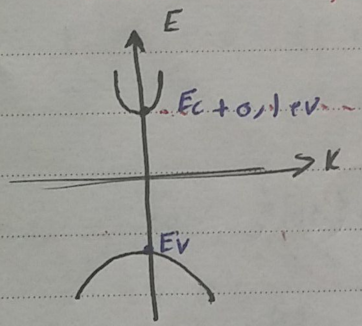
Given the mobility $\left(8500\ \frac{cm^2}{Vs} \ ,\ 400\ \frac{cm^2}{Vs} \right)$

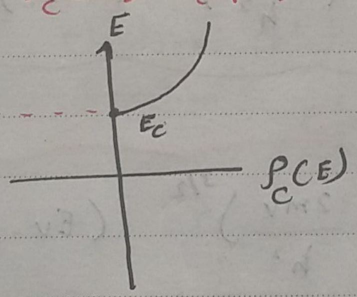
a)- Determine wich of them μ_c OR μ_v

Sol:

$\mu_c = 8500\ \frac{cm^2}{V_s}$, $\mu_v = 400\ \frac{cm^2}{Vs}$

b)- determine no. of allowed state $\rho_c(E)$ for bulk material for energy level from $E_c \longrightarrow E_c + 0{,}01\ eV$





$$\rho_c(E) = \frac{1}{2\pi^2} \left(\frac{2m_c}{\hbar^2} \right)^{3/2} (E - E_c)^{\frac{1}{2}}$$

$E > E_c$

$$N = \int_{E_c}^{E_c + 0{,}1 eV} \rho_c(E) \cdot dE$$

$$N = \int \underbrace{\frac{1}{2\pi^2} \left(\frac{2m_c}{\hbar^2} \right)^{3/2}}_{W} (E - E_c)^{\frac{1}{2}} \cdot dE$$

/ /

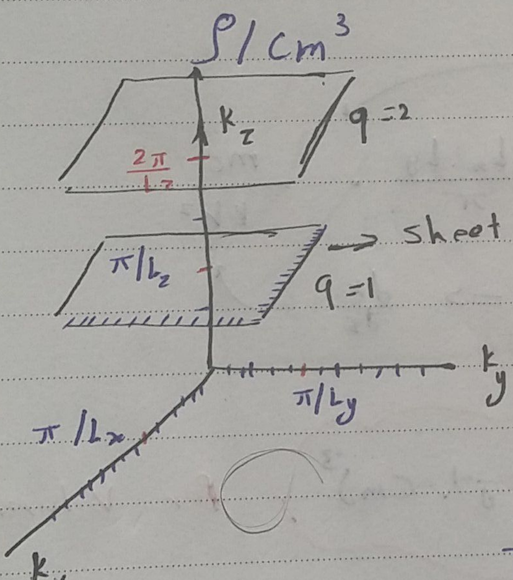
$0,1\ ev = 0,1 \times 1,6 \times 10^{-19}$ J   transfer $ev \rightarrow J$

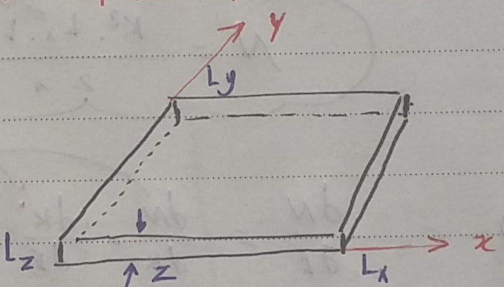
$m_c = 0,067\ m_0 = 0,067 \times 9.1 \times 10^{-31}$

$\hbar = 1,05 \times 10^{-34}$

$$N = \frac{2}{3} \times W \, (E - E_c)^{\frac{3}{2}} \Big|_{E_c}^{E_c + 0,1 ev} \approx 10^{18} / cc$$

Density of tate for Quantum well structures:





assume:

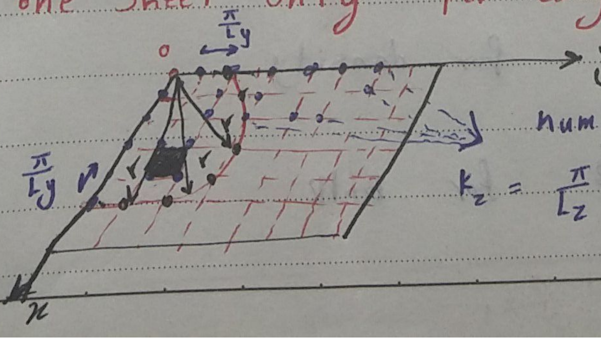
$L_y = L_x = 1mm$

$L_z = 10\ A^o$

$\frac{\pi}{L_x} = 100\pi$ $6\ \frac{\pi}{L_z} = 10^9 \pi$

$\Longrightarrow K_z =$ discrete value

with using one Sheet only for eazy calculation $(q=1)$



/ /

Area of on state $= \left(\frac{\pi}{L_x}, \frac{\pi}{L_y}\right)$

Area of all state up to E_n = Const $= \frac{\pi k^2}{4}$

$k = \sqrt{k_x^2 + k_y^2 + k_z^2}$

N = no of allowe space in k space $= \frac{\pi k^2}{4\left(\frac{\pi}{L_x}\right)\left(\frac{\pi}{L_y}\right)}$

$$\Longrightarrow N = \frac{k^2 L_x . L_y}{4\pi}$$

with taking in Consideration electron spin

$$N = \frac{k^2 . L_x . L_y}{2\pi}$$

$$\Longrightarrow \rho_c(E) = \frac{dN}{dE} = \frac{dN}{dk} . \frac{dk}{dE} = \frac{k L_x . L_y}{\pi} . \frac{m_c}{k \hbar^2}$$

from $E = E_c + \frac{\hbar^2 k^2}{2m_c} \Rightarrow \frac{dk}{dE} =$

$$\Longrightarrow \rho_c(E) = \frac{m_c}{\pi \hbar^2 L_z} \quad (J^{-1} . cm^{-3})$$

$\frac{J}{cm^3}$ = volume

Per Volume

* $\rho_c(E)$ → $1/cm^3$ → $1/cm^2$ $\Rightarrow \rho_c(E) = \frac{m_c}{\pi \hbar^2}$ per unit area

* $\Rightarrow \rho_c(E) = \frac{m_c}{\pi \hbar^2 . L_z}$ for density

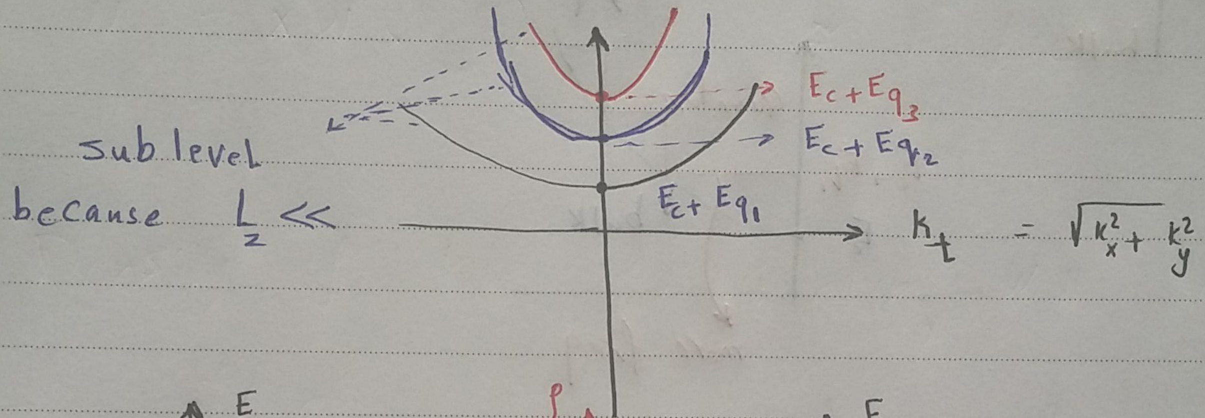
$\rho_c(E) = \frac{1}{2\pi^2}\left(\frac{2m_c}{\hbar^2}\right)^{3/2} (E - E_c)^{\frac{1}{2}}$ for bulk

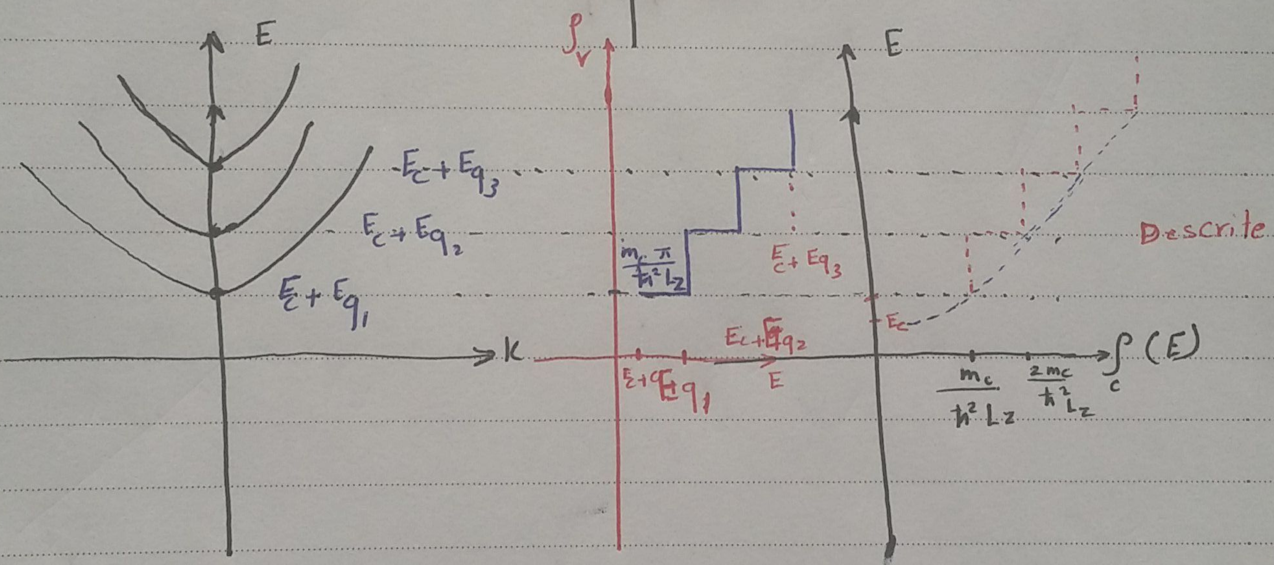
Report : density $\rho_c(E)$ for 1D (non wire)

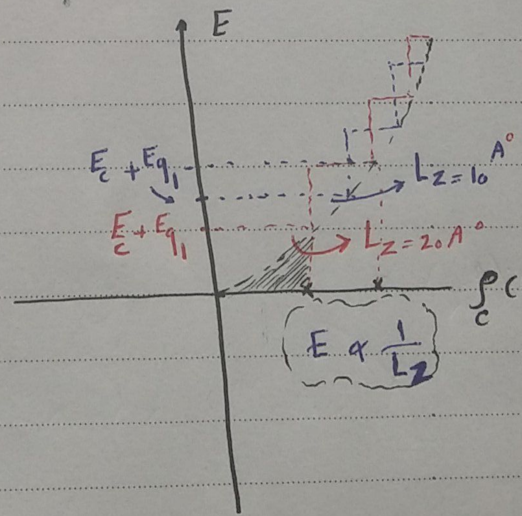
/ /

* $E = E_c + \frac{\hbar^2 k^2}{2m_c} = \frac{\hbar^2(k_x^2+k_y^2)}{2m_c} + \frac{\hbar^2 k_z^2}{2m_c}$ → const (discrete)

$$E\Big|_{q=1 \text{ (first sheet)}} = \underbrace{E_c}_{\text{Const}} + \underbrace{\frac{(\hbar^2 k_t^2)}{2m_c}}_{\text{variable}} + \underbrace{\frac{\hbar^2}{2m_c}\left(\frac{\pi \times 1}{L_z}\right)^2}_{\text{Const}} \quad E_{q_1}$$







* Quantum deal with Eenergy ↑ mor than ~~black~~ bulk

Scanned by CamScanner

difference between bulk & Quantum :